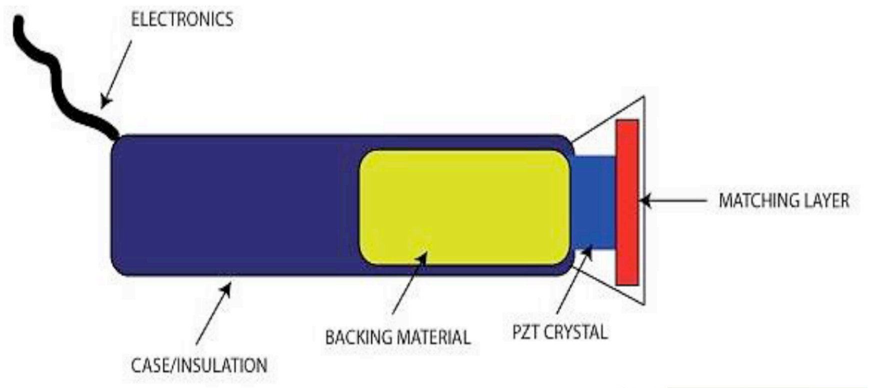
TRANSDUCERS AND PIEZOELECTRIC EFFECT

TRANSDUCERS≈PIEZOELECTRIC ELEMENTS

Transducers convert energy from one form to another and have a bidirectonal function. Electrical energy is converted by piezoelectric crystals into mechanical energy which generates ultrasound waves. Echoes return stimulating these crystals and these produce electrical signals returning to the machine. These electrical signals are converted into the grey scale imaging we see.

Basic transducer construction:



Source: Echocardiographer.org

PIEZOELECTRIC CRYSTALS AND EFFECT

Composites of ceramic/polymer are treated with high temperatures and strong electric fields to produce the piezoelectric properties necessary to generate sound waves.

- **Principle of piezoelectricity is the crystals produce a pressure when deformed by an applied voltage and produce a voltage when deformed by an applied pressure:**

  - Application of a voltage cause expansion or contraction of the crystals depending on the polarity. The crystal then resonates, converting electricity to ultrasound
  - **The frequency of sound produced is dependent on the thickness of the crystal**
  - Conversely the echoes received cause the crystals to deform producing a voltage which is analysed

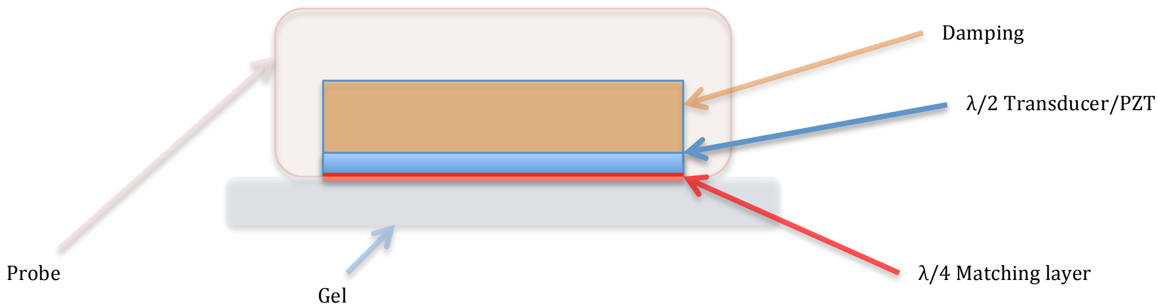
- Expansion and contraction occurs more then 20000 times a second when voltage is applied:

  - Continuous wave ultrasound is produced by continued applied voltage
  - Pulse wave ultrasound is produced by short voltage application, this causes crystals to resonate at a specific frequency
  - Higher voltages create higher amplitude (power) waves

TRANSDUCER RESONANCE AND EFFICIENCY

- Each transducer (piezoelectric transducer= PZT) has an optimum frequency of operation; this is the resonant or natural frequency:

  - Efficiency in transmission and reception is optimal at resonant frequency
  - For a specific frequency of operation the ultrasound wavelength λ is calculated
  - Resonance is achieved by making the piezoelectric crystal layer exactly ½ this wavelength in thickness



- **Damping or backing layer:**

  - Once applied voltage to transducer ceases damping helps to reduce continued oscillation of transducer at resonant frequency, this ensures transmit pulses remain short in duration
  - Maintaining short transmit pulse duration improves spatial resolution
  - As a result of shorter pulse transmits damping helps to increase a transducers bandwidth (Can detect wider range of frequencies)
  - Damping also inhibits ultrasounds travelling back into probe causing interference
  - As a compromise for shortened transducer oscillation the damping also reduces intensity, so a balance is required between the two

- **Matching layer and acoustic impedance matching:**

  - A matching layer is placed between transducer and skin surface which helps to reduce acoustic impedance difference; thereby reducing reflection and increasing transmission at this interface
  - Mathematically this can be shown to be achieved with a matching layer the thickness of $\lambda/4$
  - The matching layer also aids in damping adding to the improved transducer bandwidth

- **Ultrasound gel:**

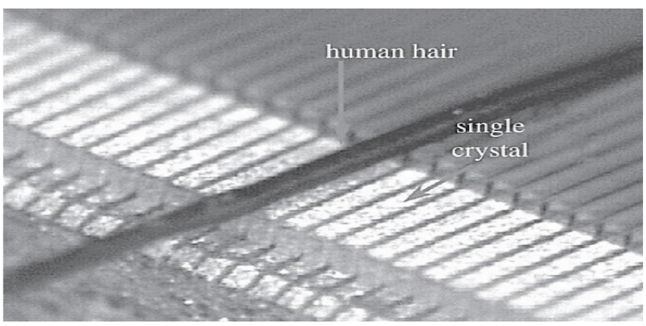
  - Gets rid of air between skin and probe surface
  - Air is a very strong reflector cause poor transmission of the ultrasound waves and giving significant image degradation

MULTI ELEMENT TRANSDUCERS

Ultrasounds use array transducers made of multiple independent transducer elements formed from the piezoelectric material.

Multiple cuts are made along the length of the transducer allowing each element to operate as a separate transducer:

- Each individual element is acoustically and electrically isolated, allowing flexibility in beam formation
- This array structure allows electronic steering and focusing of the beam
- The elements combine to form a single wave front; this is known as Huygens Principle



Source: Josefa Paredes- Back to Basics Ultrasound (Royal Brompton Hospital)

ARRAY PROBE TYPES

Source: Josefa Paredes- Back to Basics Ultrasound (Royal Bromptonm Hospital)

- Linear array:
  - Typically 256 elements
  - High frequency and wide bandwidth (2.5-12 MHz)
  - The beam is stepped from left to right for successive transmit pulses forming a rectangular field of view
  - Used for imaging at flat surfaces, superficial structures at high resolution

- Curvilinear array:
  - Similar to linear array except lines of sight are not parallel due to curved probe face
  - Mid range frequency and bandwidth (2.5-7.5 MHz)
  - Produces a radial field of view allowing imaging at depth
  - Used for abdominal scanning/organ scanning

- Phased array:
  - Typically 64 or 128 elements
  - Small square footprint allows imaging in smaller acoustic window
  - Fixed beam point of origin with steering of the beams from this origin to form image
  - Results in excellent field of view at depth but very limited information within the superficial field
  - Used in echocardiography (small acoustic windows of the intercostal spaces)

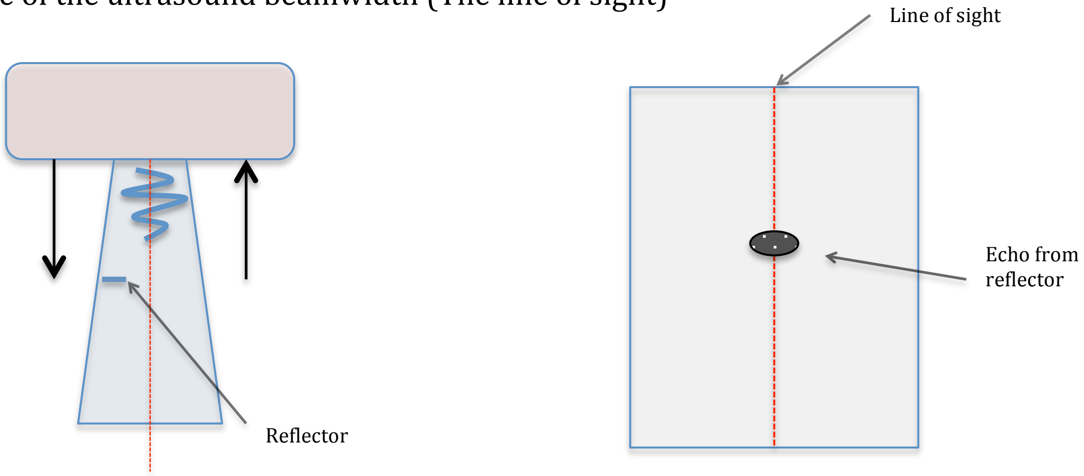
- Invasive probes trans-oesophageal, trans-vaginal, trans-rectal:
  - Use same array structure and technology

- 3D probes:
  - Elements split over length and width of the transducer allowing focusing and steering in scan plane and across the width of the transducer

BEAMWIDTH, SLICE THICKNESS AND FOCUSING

A reflector or scatterer will produce an echo when within the beam of the transducer, the position is based on a known beam position and the pulse echo principle where depth is proportional to the time of reception of a echo for each transmit.

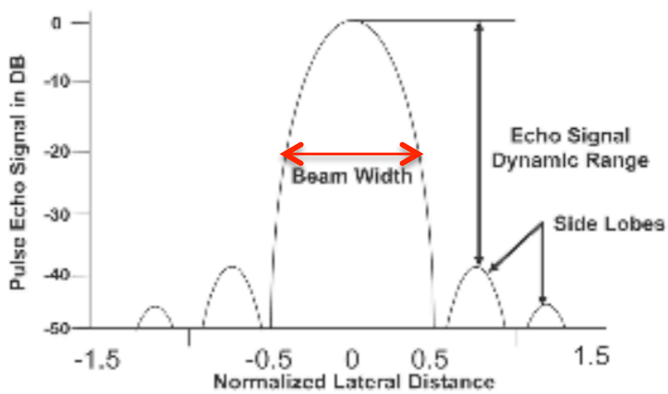
- Ultrasound machines assume any echoes received from an object are in the midline of the ultrasound beamwidth (The line of sight)



- A narrow beamwidth ensures a more accurate positioning of echoes from a reflector
- Focusing at a chosen depth helps to narrow the beamwidth within the zone of interest

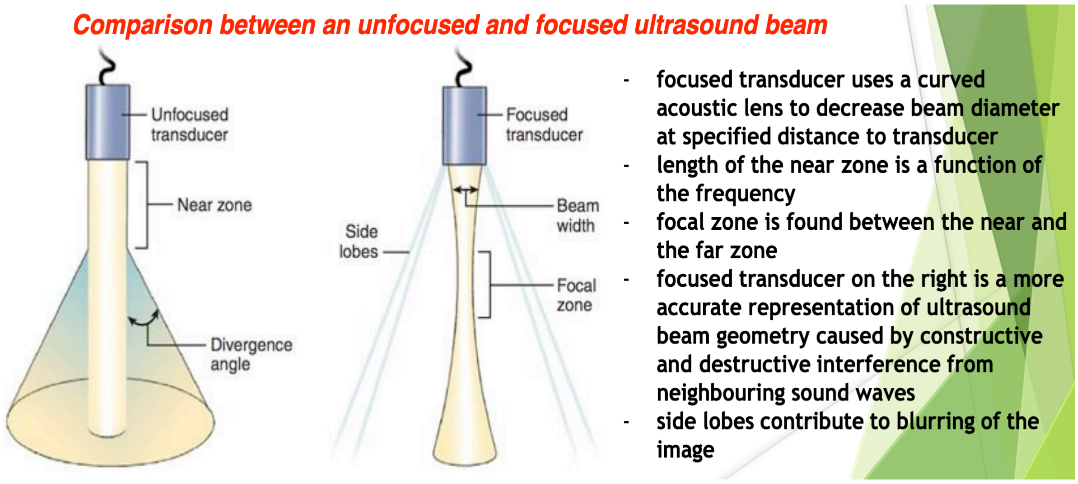
BEAMWIDTH

The boundaries of the beamwidth are determined by a 20dB reduction in intensity by an ultrasound machine



Source: Powis et al. - Journal of Diagnostic Medical Sonography (2004)

UNFOCUSED TRANSDUCER AND FAR FIELD BEAMWIDTH



Source: Josefa Paredes- Back to Basics Ultrasound (Royal Brompton Hospital)

An un-focused transducer beam undergoes self-focusing forming a near field (Fresnel Zone) and far field (Fraunhofer Zone).

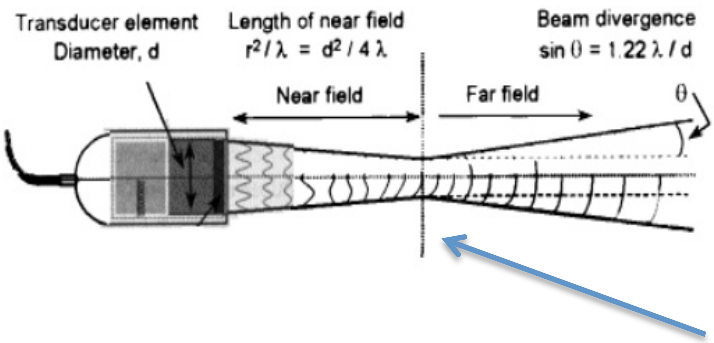
- In the far field (FRAUNHOFER ZONE) beamwidth is determined by the **diffraction limit**:

  - Diffraction limit is the narrowest beamwidth at a certain depth
  - This is defined by the divergence angle θ

- For a large-area single-element transducer, the angle of ultrasound beam divergence, θ, for the far field is given by

$$\sin\theta = 1.22\frac{\lambda}{d}$$

  - where *d* is the effective diameter of the transducer and λ is the wavelength; both must have the same units of distance.



Source: Rakesh Ca- Ultrasound Physics

Beamwidth = d/2

Therefore in the far field:

$$\text{Divergence } \theta = \sin^{-1} \left({}^{1.22\lambda}/_{d} \right)$$

$$\text{As } f = {}^{c}/_{\lambda}$$

- **Higher frequency will mean a smaller divergence angle and therefore a narrower beamwidth**
- **A wider transducer aperture means a smaller divergence angle and narrower beamwidth**

UNFOCUSED TRANSDUCER AND NEAR FIELD

In the near field the beamwidth is wider then the diffraction limits, and narrows to a beamwidth ½ the transducer aperture (d/2) at the transition to the far field

- NZL is the transition distance from the near field to far field which occurs when beamwidth is ½ the transducer aperture:

    - Important parameter in design of focused transducers
    - **It is only possible to focus at a depth that is within this near zone length**

$$NZL = d^2/4\lambda$$

- **High frequency and wide transducer aperture means a larger NZL**

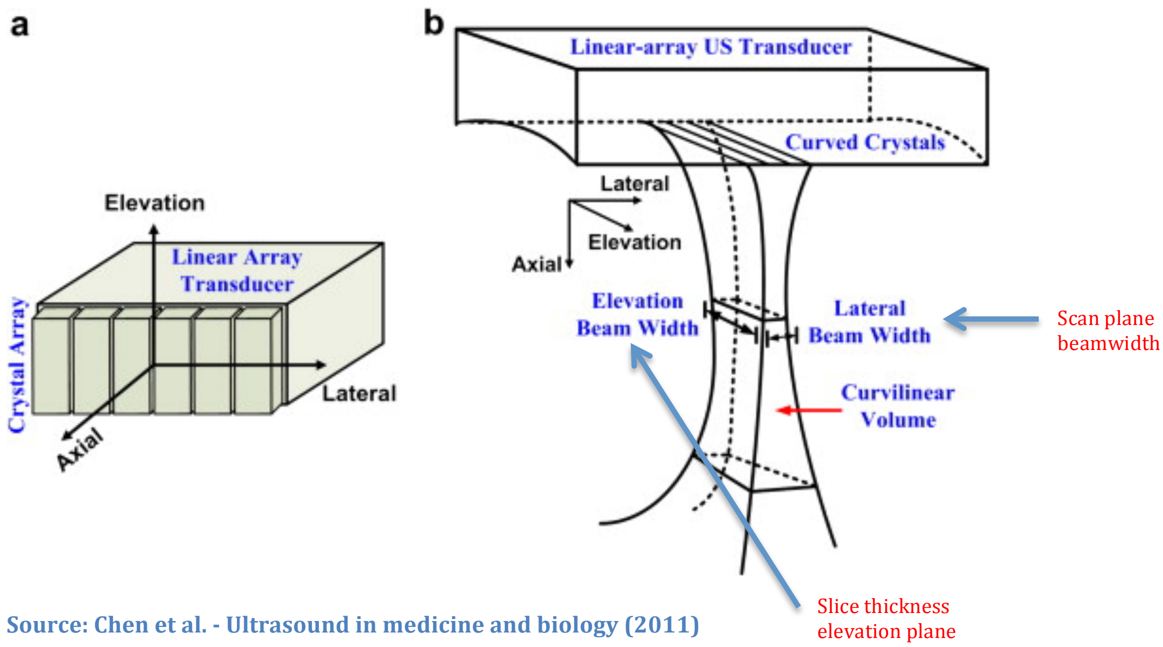
    - **These are the same parameters that keep the beamwidth small in the far field**

FOCUSING

Focusing will be most successful if the frequency is high and or the transducer aperture is large equating to a larger NZL, there are obvious physical limits on both of these factors.

Focusing of the transducer can be achieved through a number of methods:

- Curved transducer face or the use of an acoustic lens are traditional
- Acoustic lenses are still used to help focus in the slice thickness plane
- Electronic focusing is the mainstay in scan plan (beamwidth) focus

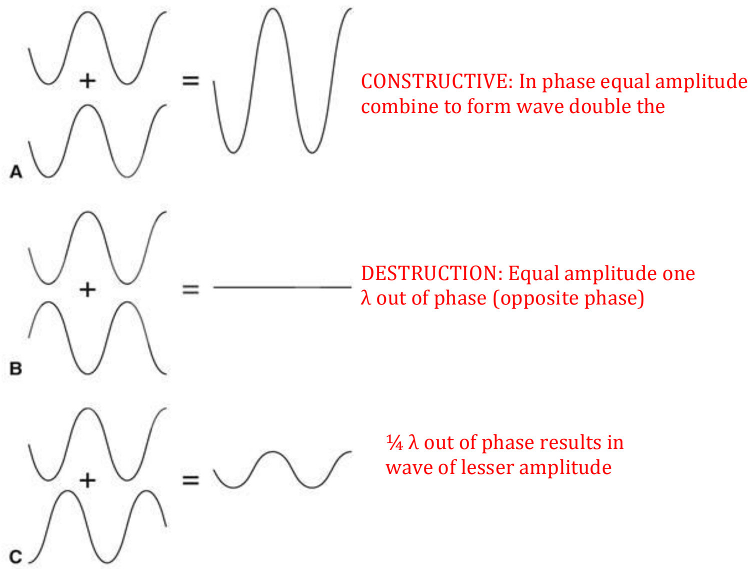


Source: Chen et al. - Ultrasound in medicine and biology (2011)

HUYGENS' PRINCIPLE AND SUPERPOSITION

Two important principles for understanding focusing:

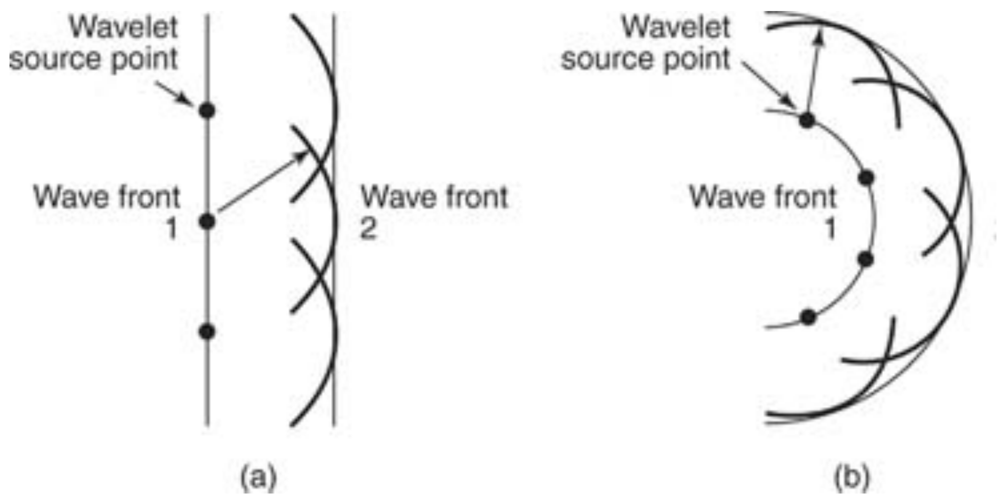
- SUPERPOSITION
  - Superposition occurs when two or more waves arrive at a single point resulting in constructive, a combination of, or destructive interference
  - The combination of the waves depends on their relative phase to each other and the amplitude of the waves



- HUYGENS' PRINCIPLE

    - The transducer acts a source of a large number of point sources of ultrasound energy
    - Each point source emits wavelets of radial energy, it has no specific beam pattern, spreading equally in all directions (like a pebble dropped in water)
    - These wavelets combine to produce a wavefront

Every point on a wavefront acts as a source of tiny wavelets that move forward with the same propagation speed as the wave. The wave front at a later instant is the surface that is tangent to the wavelets.



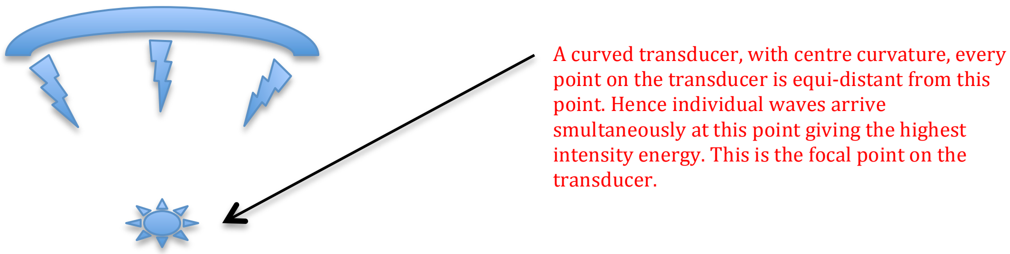
Source: physics.stockexchange.com

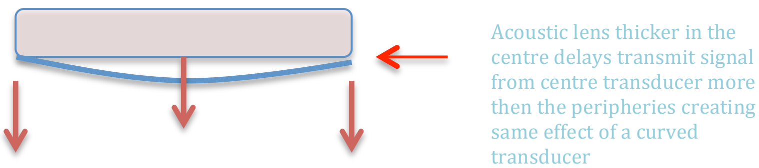
FOCAL POINT, BEAM INTENSITY AND BEAMWIDTH

- Contributions at a point at depth from each transducer transmit source will interact in a constructive or destructive pattern depending on the phase of the waves at this point of arrival (SUPERPOSITION)

- The intensity of energy at this point will depend on the combination of these waves. To ensure maximum intensity at a chosen focal position the waves need to be in phase to ensure a constructive pattern ie. They need to arrive at the same time.

- This can be achieved by using a curved probe face, an acoustic lens, or electronically to delay transmits from particular parts of the transducer face.





- Intensity is defined as the power per unit area

- Intensity and beamwidth are related; as the beamwidth is narrowed at a depth the intensity must increase:

- as intensity increases at a certain depth the beamwidth must narrow
- as beamwidth narrows intensity increases

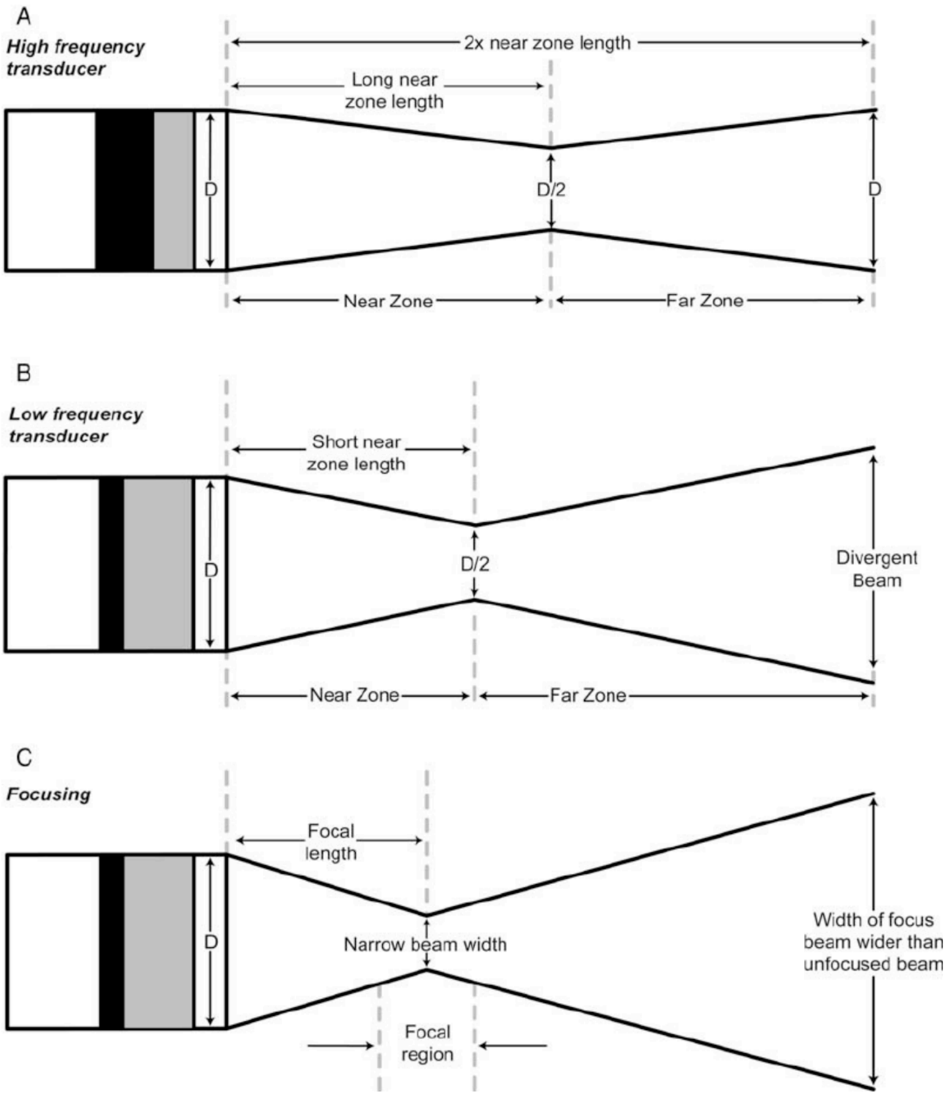
Therefore:

The focal point is the depth where the intensity is greatest and the beam is at its narrowest.

FOCUSED TRANSDUCER

A focused transducer has a focal zone with a narrowed beamwidth over the length of this zone. For a transducer at the same frequency, the focal depth will have an effect on focal zone length, beamwidth and degree of beam divergence beyond the focal zone in the far field:

- A superficially, or strongly focused, transducer will have a shorter focal zone with a narrow beam, and a more pronounced beam divergence beyond the focal zone
- With a less superficial focus, the focal zone will be longer, beamwidth larger, and beam divergence less pronounced beyond the focal zone.



(A) High-frequency transducer with long near-zone length and narrow beam width. (B) Low-frequency transducer with short near-zone length and wide beam width. (C) Focusing narrows beam width.

Source: Swanevelder et al.- Resolution Ultrasound Imaging. Continuing Education Anaesthesia and Critical care (2011)

- Beamwidth at focus is determined by the diffraction limit:

D = depth of focus
A= transducer aperture

Beam width at focus= ${}^{2.44\lambda D}/_{A}$

Therefore:

- **the highest possible frequency and largest aperture transducer will result in the smallest beamwidth at focus**
- **beamwidth has significant impact on resolution**

ARRAY TRANSDUCER ELECTRONIC FOCUSING

PHASED ARRAY

In phased array the origin of the beam is fixed and scanned by steering the beam in series of different directions to form an image

- Phased array transmit

- Focussing is achieved by all the transducer elements contributing to the transmit pulse, but each element transmits at a slightly different time, this is effected by an inbuilt electronic delay system
- This delay creates a simulated curved focused transducer with outer elements transmitting first and central elements last
- Each of the 128 elements in the array will have its own electronic delay
- The focusing of the array and 90^{o} beam steering across multiple lines of sight combine to create an image
- About 90 transmit pulses are required to create an image

- **Phased array receive focusing:**

- similar delays occur for received echoes with the central echoes returning first undergoing the longest electronic receive delays
- this ensures echoes received will be in phase, maximising echo strength and ensuring a narrow receive beamwidth

- recieve focusing is automatic and dynamic, the machine adjusts the receive focus delays so that its is focused at the depth the echoes are returning from

- the aperture of the transducer used to receive echoes is also dynamically varied and increases to a maximal point as the depth from which the echoes return from increase.

LINEAR ARRAY

Typically made up of 256 elements. Each beam is created by a subset of elements of around 128 elements. Each new beam is created by a new subset stepped one element (ie 1-128, then 2-129 then 3-130 ……) along the transducer to create 129 lines of sight.

- Standard linear array imaging each line of sight is parallel
- Beam steering is utilised in additional modes such as doppler modes and compound imaging (multiple beams steered at different directions to produce a combined image)
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CURVILINEAR ARRAY

Similar to linear array buy curved transducer creates a radial field of view

KEY POINTS

PIEZOELECTRIC EFFECT

- Principle of piezoelectricity is the crystals produce a pressure when deformed by an applied voltage and produce a voltage when deformed by an applied pressure.
- Maximal efficiency is at resonant frequency; this is achieved by ensuring the crystal layer thickness is ½ the wavelength dimension of the desired frequency

BEAMWIDTH, FOCUSING

- Ultrasound machines assume any echoes received from an object are in the midline of the ultrasound beamwidth (The line of sight).

- Beamwidth is an important determinant of resolution, in particular lateral resolution.
- Narrow beamwidth is achieved by higher frequency and larger transducer aperture.

- A beam will undergo self-focusing forming a near field zone, with a near zone length (NZL), and far field.

- It is only possible to focus within the NZL
- High frequency and wide transducer aperture means a larger NZL
- Focusing will be most successful if the frequency is high and or the transducer aperture is large

- Focal point:

- The focal point is the depth where the beamwidth is narrowest and the intensity of the beam is the greatest.

FOCUSED TRANSDUCER

- A focused transducer will have a focal zone with a narrowed beamwidth over a certain length.

- A strongly/superficially-focused transducer will have a short focal zone length, a very narrow beamwidth at the focal zone, but will suffer rapid beam divergence beyond the focal zone.
- Beamwidth at focus is determined by the diffraction limit, and therefore a narrow beamwidth is achieved by a higher frequency and larger transducer aperture

REFERENCES

The Physics and technology of Diagnostic Ultrasound: A Practitioner's Guide. By Dr Robert Gill.

Artifacts in Diagnostic Medical Ultrasound: Volume 1 Grayscale Artifacts. By Martin Necas

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